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Development and Performance Test of a 100hp HTS Motor

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Abstract-- **This paper describes the development and fabrication of a high temperature superconducting motor which consists of HTS rotor and air-core stator. The machine was designed for the rated power of 100hp at 1800 rpm. The HTS field windings are composed of the double-pancake coils wound with AMSC's SUS-reinforced Bi-2223 tape conductor. These were assembled on the support structure and fixed by a bandage of glass-fiber composite. The cooling system is based on the heat transfer mechanism of the thermosyphon by using GM cryocooler as cooling source. The cold head is in contact with the condenser of a Ne-filled thermosyphon. The rotor assembly was tested independently at the stationary state and combined with stator. Characteristic parameters such as reactances, inductances, and time constants were determined to obtain a consistent overview of the machine operation properties. This motor has met all design parameters by demonstrating HTS field winding, cryogenic refrigeration systems and an air-core armature winding cooled with air. The HTS field winding could be cooled down below 30K. No-load test of open-circuit characteristics(OCC) and short-circuit characteristics(SCC) and load test with resistive load bank were conducted in generator mode. Maximum operating current of field winding at 30K was 120A. From OCC and SCC test results synchronous inductance and synchronous reactance were 2.4mH, 0.49pu, respectively. Efficiency of this HTS machine was 93.3% in full load(100hp) test. This paper will present design, construction, and basic experimental test results of the 100hp HTS machine.**

1. INTRODUCTION

With the advent of high-temperature superconducting material such as BSCCO and the availability of the robust HTS wire in industrially applicable length, the several electrical power devices including motors, generators, transformers, fault current limiters, and power transmission cables have been demonstrated, and is expected to have the industrial viability. Moreover, with higher cooling temperature than LTS and availability of highly reliable cryocooler on the shelf, their industrial application will be realized in the near future. As well known, advantages of the superconductivity could make the machine more efficient and compact with significant energy saving. In the case of the motors, especially, the benefit of using the superconductors can be represented by the reduction of 50% in both losses and size compared to conventional motors of the same rating, which is resulted from the high magnetic field generated by field winding wound with superconducting wire[1]. The smaller motor size also reduces friction and windage, and the amount of the losses in the armature material.

According to potential of the several advantages and industrial application of the HTS motor, HTS motor development projects started from middle of the 1990's in USA[2,3] and 2000 in Germany[4]. Development program of the superconductivity application has been launched on 2001 in Korea, in which HTS motor is one of the development target. In the phase I of this project, KERI(Korea Electrotechnology Research institute) has developed 100hp synchronous superconducting motor in order to explore it's potential, with specific goals of testing the feasibility of concepts such as a designing technique, a rotating superconducting field winding and closed cycle cooling system. This paper summarizes the development of the 100hp motor in Korea.

2. DESIGN AND CONSTRUCTION OF THE 100HP MOTOR

2.1. Design of 100hp HTS motor

The prototype 100hp motor was designed, based on the 2-dimensional magnetic field analysis, and each machine parameter is obtained and summarized in Table 1[5]. The cross-sectional sketch is drawn from the program results as shown in Fig.1.

TABLE I
SPECIFICATIONS OF A 100[HP] HTS MOTOR.

Rating Capacity	100[HP]
Rating Speed	1800[rpm]
Pole Number	4
Armature Terminal Voltage	380[V]
Power Factor	1.0
Frequency	60[Hz]
Synchronous Reactance	0.5[p.u.]
Field Coil Operating Current	100[A]
Field Coil Turn Number	500[turns/pole]
Armature Rating Current	119[A]
Armature Turn Number	80[turns/phase]
Armature Slot Number	24
Direct Axial Length	250[mm]
Machine Shield Outer Diameter	478[mm]

The machine shield inner diameter is 210mm as large as there is enough vacuum space inside of rotor and as small as enough machine output can be obtained by small flux leakage between rotor and stator coils. The armature coils fill 55% of slot geometry composed of Fiber Reinforced Polymer (FRP) composite having the same permeability with air. The rating current density of the armature conductor is $3A/mm^2$ enough to cool the coils only with forced air flow [2].

The cylindrical damper that locates between the field and the armature coils protects the HTS coils from transient magnetic field generated by the armature coil at starting and fault conditions. Moreover, it produces starting torque and prevents the motor from losing synchronism by inducing eddy current like an induction motor.

The designed 100hp motor was fabricated using the American superconductor's multifilamentary composite HTS wire. The motor undergoing performance testing after assembly is shown in Fig. 2. The rotor assembly includes HTS field winding operating at cryogenic temperature (30K), torque tubes made with G10, rotor cryostat, refrigeration component, and damper. The stator assembly include stator winding, machine shield, stator winding support structure, bearing and housing.

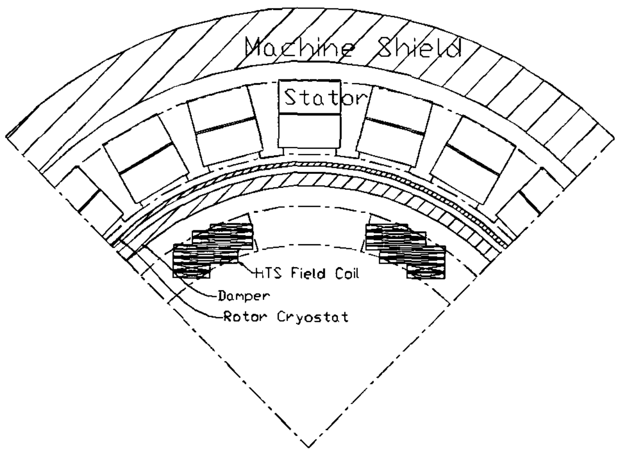

Fig. 1. Cross-sectional diagram of the designed 100[HP] HTS motor.

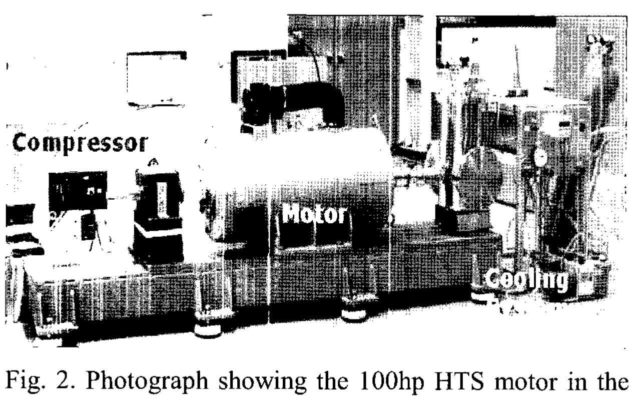

Fig. 2. Photograph showing the 100hp HTS motor in the test bed. The cooling system with the cryocooler is located in the right side.

2.2. Performance of the Field Coil Assembly

The basic design of the field winding is quadrupole, and four sets of windings were fabricated for this machine. The windings are composed of the double pancake racetrack coils of Bi-2223 conductor. Each of these polesets is comprised of 4 double pancakes of different number of turn yielding nominal 500 turns per poleset.

Fig. 3 shows the assembled field winding, I-V test results of field windings. The I-V test was conducted on the condition that the current is supplied at 1A/sec rate and at 77K with no external field. The critical current of the total field coil is 41A with each coil connected in series. Fabrication and test results of field winding were reported at reference [6] already. From the study of J.-T. Eriksson et al., Ic at 20.4K was 4.8 times as large as Ic at 77K [7]. It is expected that Ic at 30K will be four times as large as Ic at 77K. Therefore it is expected that the operating current(100A) could be easily achieved at about 30K. Each field coil revealed almost the same I-V characteristics. The winding support structure is made with non-magnetic aluminum ally of which conduction heat property is excellent. We used the wet winding technique with carefully controlled tension to manufacture a set of coil that shows uniform in dimensions. Each field winding is finally enclosed with aluminum cover, and impregnated with epoxy resign to enforce the field coil assembly against the centrifugal force and other mechanical disturbance. After assembling all of the cold mass, it was balanced in order to limit the mechanical load on the elements connecting the cold mass to the room temperature flange of the shafts. The torque tube which transfer torque from the field coil to external load or vice versa also connects cold mass to room temperature drive end shaft, so it has to be designed not only to withstand torsional load with an order of magnitude larger than nominal but also to minimize the heat conducted into the cold region. Grass-fiber reinforced plastics(G-10) is selected as torque tube material, and its dimensions are calculated from FEM analysis in the condition of a three-phase short circuit fault on the motor. For the security of the machine torsional performance test was conducted by using the same one. Mechanically the two shafts are connected by cylindrical outer cryostat wall which serves as the vacuum chamber, and the sliding mechanism was

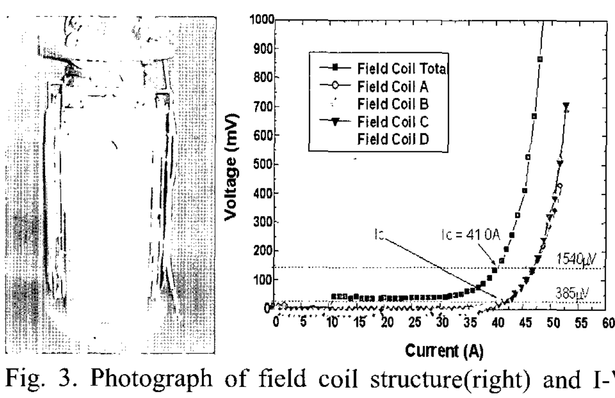

Fig. 3. Photograph of field coil structure(right) and I-V characteristics of the each and serially connected coil(left).

adopted to one of the connecting part for the compensation of the mechanical shrinkage during cool down. Fig.4 shows the completed rotor with HTS coils installed and outer vacuum jacket.

Another important parameter which must be considered in rotating machine is the vibration characteristics of a rotating part, and vibration harmonics of finally assembled rotor were measured. As shown in Fig. 5, 5^{th} order peak occurred at 960rpm and 4^{th} order peak at 120rpm. The machine could be safely operated in the range form 0 to 1800rpm, as the critical speed was calculated as 4800rpm.

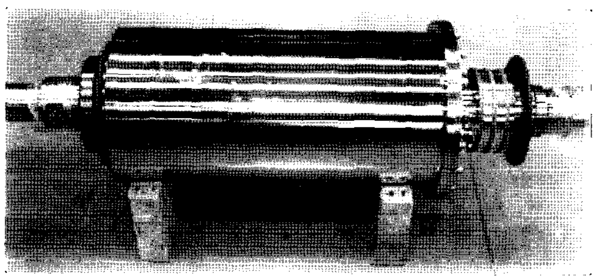

Fig. 4. The completed rotor with HTS coils installed and outer vacuum jacket.

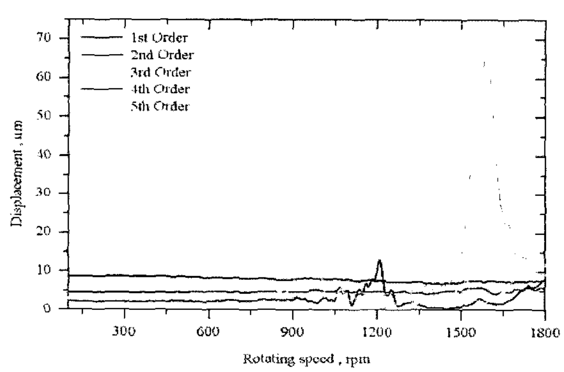

Fig. 5. Order-tracking vibration of HTS motor.

2.3. Stator Development

The stator design differs substantially from that of the conventional one in order to fully utilize the advantage of HTS field winding. The air core winding type was chosen because the high magnetic field generated by HTS field winding would saturate the steel laminations, and it could result in the increase of the motor efficiency and decrease of the volume. As iron teeth are not existent, the reaction force from field winding are supported by non-magnetic and 5mm-thick GFRP structure in which 5mm-wide air duct was installed in axial direction yielding 27 total ducts in order to dissipate efficiently the generated heat in the stator windings. The cross-sectional diagram of the stator coil structure is shown in Fig. 6. The stator conductor is comprised of 16 strands of 1.6mm diameter copper wire of which current density is 3.7A/mm^2. The stator is air-cooled, and the current density in the stator conductor is below the nominated 6A/mm^2 in the conventional air-cooled machine.

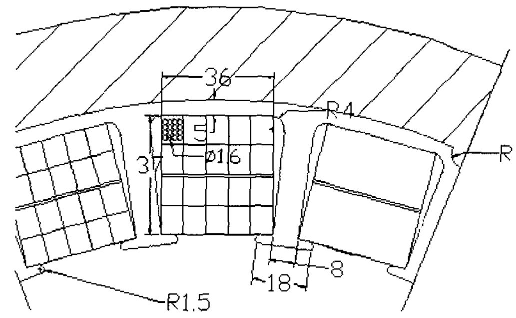

Fig.6. The cross-sectional diagram of the stator coil.

2.4. Rotor Cooling System

The cryogenic cooling system is one of the most important components in HTS motor because the machine efficiency and the system reliability substantially depends upon it. The basic concept of rotating cryogenic cooling system is based on the principal of the thermosyphon which uses the latent heat of a boiling fluid to transfer heat at very low temperature gradient. It consisted the heated region(evaporater) within which the liquid working fluid is evaporated to absorb the heat from the cold structure by conduction heat transfer and the cooled region(condenser) within which the gas is recondensed. The vacuum jacketed tube was connected between the evaporator and condenser, through which the condensed liquid flows into evaporator by gravity and evaporated gas returns to the condenser again. Another key technology of this cooling system is reliable connecting part between the rotating evaporator(inner side of field coil support) and non-rotating tube system which is connected directly to the condenser and the cold head. A rotating gas seal bearing is installed for this purpose by using hollow shaft rotary feedthru with bore diameter of 2 inch. We used Ne as working fluid, and the cooling temperature is 25 - 30K. The refrigerator for condensing Ne gas is the Gifford-McMahon type, manufactured by Leybold Vakuum GmbH, can provide a cooling power of 45W@27K. Temperature is maintained by a feedback loop controlled heater on the cold head.

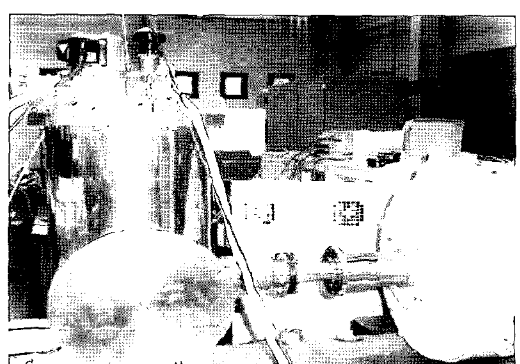

Fig. 7. Photograph of rotating cryogenic cooling system and connection between the rotating and non-rotating part of the machine.

2.5. Rotor Cooling Down

By using above mentioned cooling system, cooldown of the machine from the room temperature to operation temperature may be accomplished in 66 hours. The temperature variations of the several points in the inner part of the rotor are plotted in the Fig. 8. Temperature on the torque tube is maintained at 260K, and it is well operated to prevent heat transferring from the room temperature connection parts.

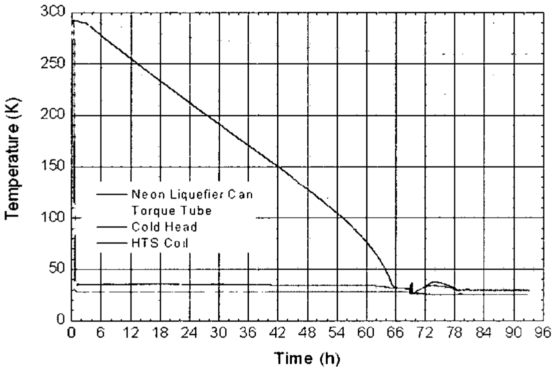

Fig. 8. The temperature variations of the several points in the inner part of the rotor.

3. PERFORMANCE TEST

We have performed a large variety of experiments to identify relevant parameters of the machine and assess the correspondence of the design parameters calculated from the developed program with experimental ones, and to establish the key technology for development of further larger class machine. These experiments were performed in our test bed consisting of data acquisition system and dynamometer which can serve as a mechanical load as well as drive for the HTS machine and another thermal resistor load bank is prepared for the generation mode test. We can also drive the HTS machine via specially manufactured inverter.

3.1. No-load and Short-Circuit Characteristics

Firstly we measure electromotive force of the armature terminal with increasing the field coil current of the HTS machine. It is found that the electromotive force increase linearly without any saturation and it is one of the advantages of the ironless machine. In the open circuit test the armature voltage showed 380V, which is the nominal value, and its shape is almost perfectly sinusoidal. This results from the fact that the rotor is made from fully non-magnetic materials, so there is no distortion coming from the iron slot in the conventional machine. From the no-load, open circuit test and the sustained short circuit test, synchronous inductance is calculated to 2.4mH, and it corresponds that synchronous reactance is 0.49pu. Stator output voltage, no-load, and short circuit characteristics are shown in Fig. 9

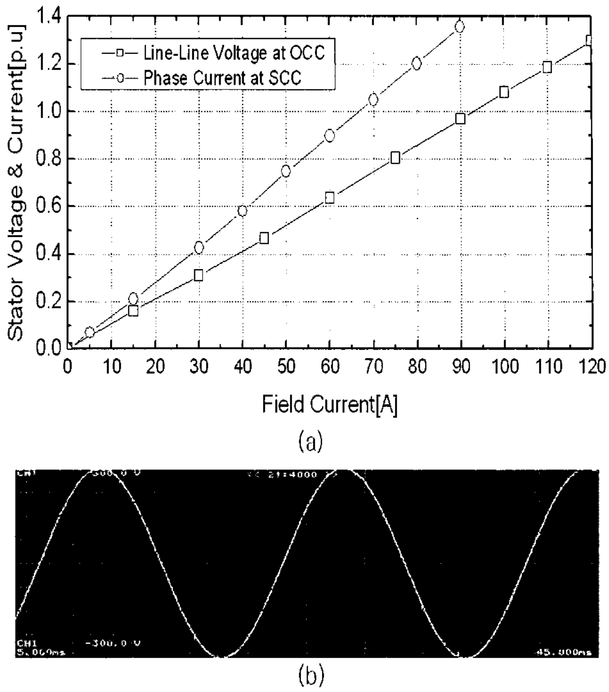

Fig. 9. No-load, short circuit characteristics(up), and three phase voltage curve(down).

3.2. Generator Mode

In this mode, the HTS machine is driven by dynamometer to see its generating characteristics at the speed of 1800rpm. In this experiment resistor load bank was connected to the stator terminal of this machine. During generator mode test, the machine efficiencies were measured as pure resistive load increases. The efficiency was above 90% and did not decrease at small resistive load condition such as 25% of the nominal capacity. As the load increases, the efficiency showed almost constant value of 93%. The efficiency characteristics of this machine are shown at Fig. 10.

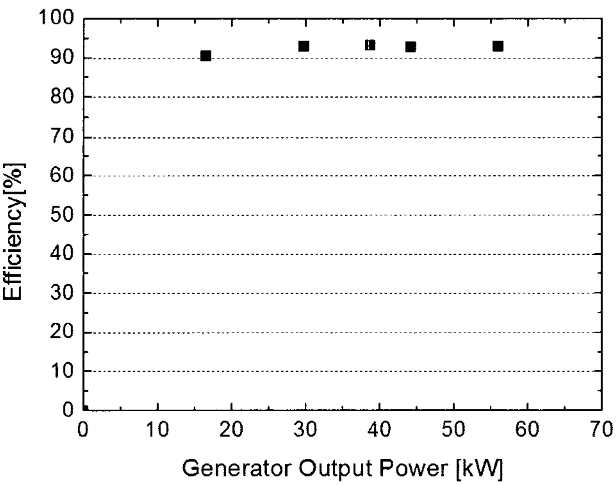

Fig. 10. Efficiencies vs. output power of the HTS machine in resistive load condition.

3.3. Motor Mode

With a help of vector control driving methodology, machine efficiencies were measured at various load conditions under the 1800rpm rotating speed, the 100A field current and the 380V stator terminal voltage. As shown in Fig. 11, electrical efficiency of this machine without considering cooling power loss is maintained relatively high from 25% load to 100%(100hp). This high efficiency at partial load is not shown in the conventional synchronous machine with iron core. The efficiency of the machine is not so high to be expected, and this may be originated from the fact that the design is not optimized and there was relatively large amount of the copper wire in the circuit because of minimization of the superconductor wire length. The motor was operated near the design power factor, 1.0, from 50% load to 100% load during the test. At full load test, torque and electrical efficiency of this HTS motor was 400Nm, 93.3%, respectively.

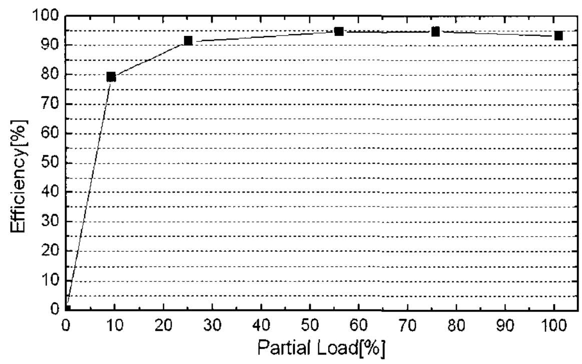

Fig. 11. Measured machine efficiencies at 0, 25%, 50%, 75% and 100% of full load(100 hp).

4. CONCLUSION

The results from the development of 100hp HTS machine well met the goal of the DAPAS(Dream for Advanced Power system by Applied Superconductivity technologies) program in Korea. The final target of this program is to pave the way for realization of the HTS motor. In phase II, the larger capacity HTS motor will be developed closer to commercialization on the base of the first phase achievement. The rotating HTS field coil was built, and cooled down below 30K by the cryogenic rotating cooling system which consists of GM cryocooler and thermosyphon type cooling system. The rotating gas seal bearing was well operated to insure operation of the rotating cryogenic cooling system, and other rotor components also were successfully operated including low heat leak torque tube. The air-gap stator was also designed, built and successfully operated at several mode and long time operation. Efficiency of this HTS machine was 93.3% *in full* load(100hp) test. With a help of vector control driving methodology, the developed 100 hp HTS motor could start rotation without problems and be tested over full load conditions.

ACKNOWLEDSMENT

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